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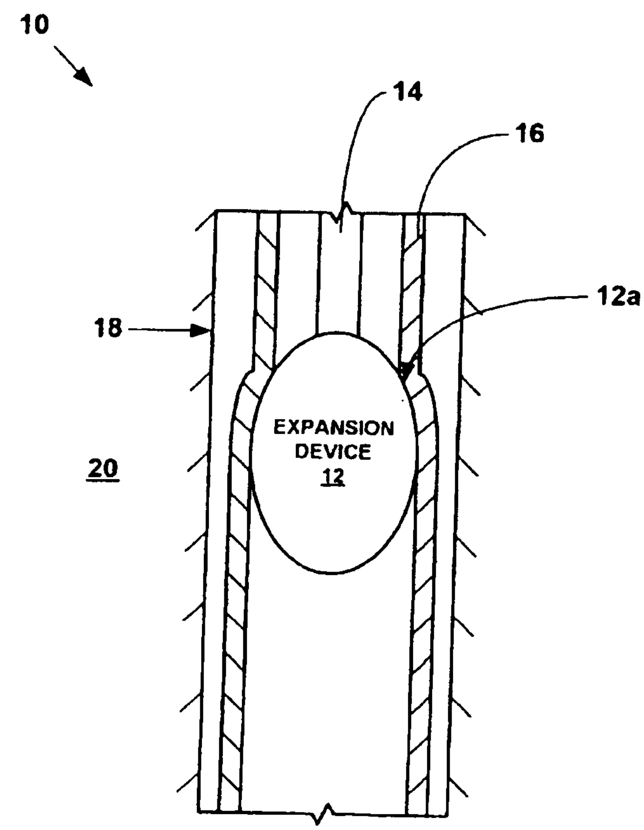


Fig. 1a

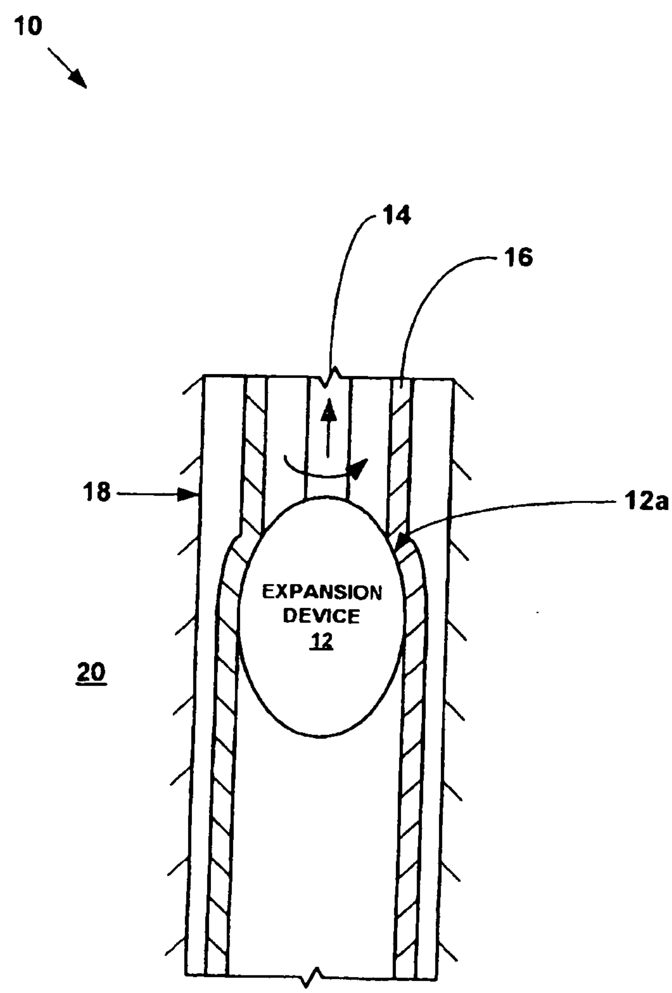


Fig. 1b

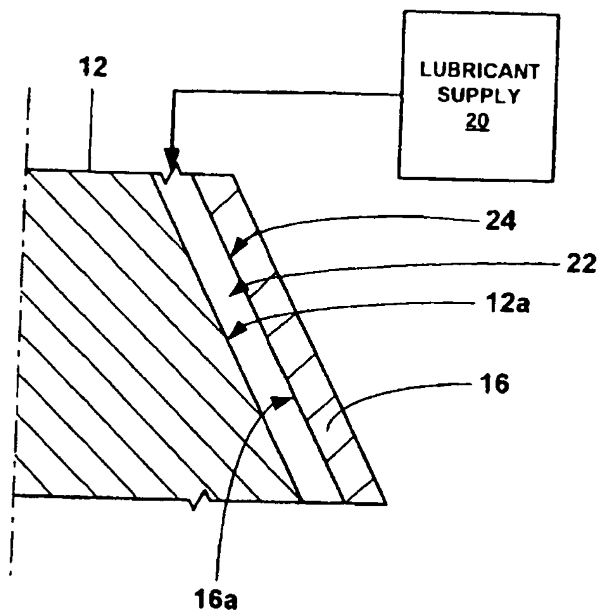
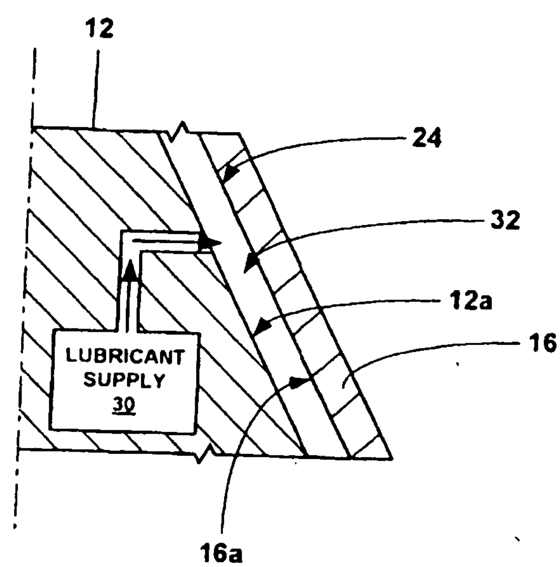

12
LUBRICANT
SUPPLY
20
24
22
12a
16
16a

Fig. 2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24
32
12a
16
LUBRICANT
SUPPLY
30
16a

Fig. 3

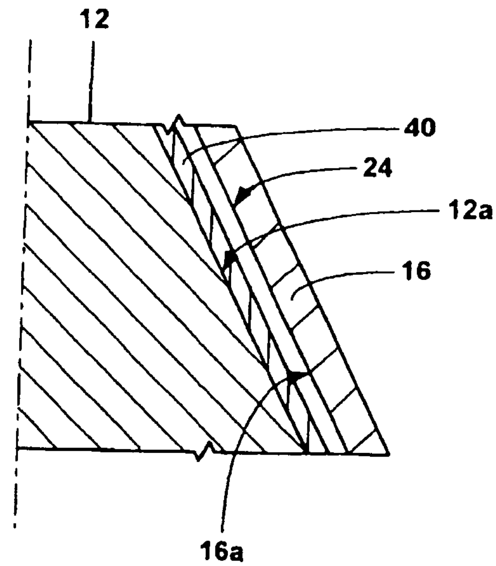


Fig. 4

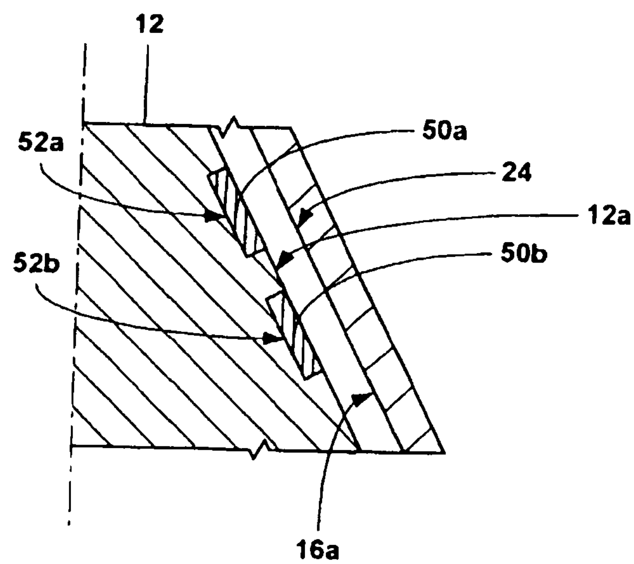


Fig. 5

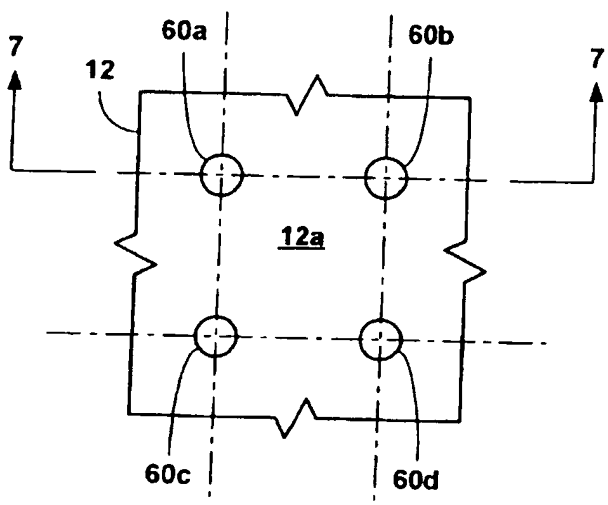


Fig. 6

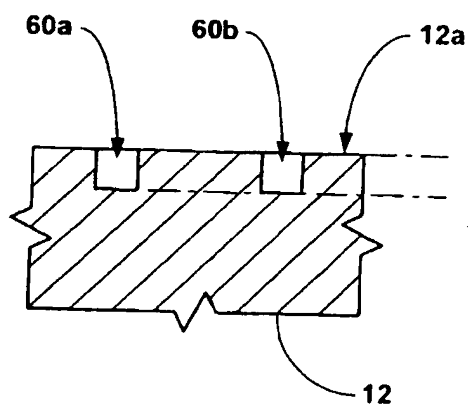


Fig. 7

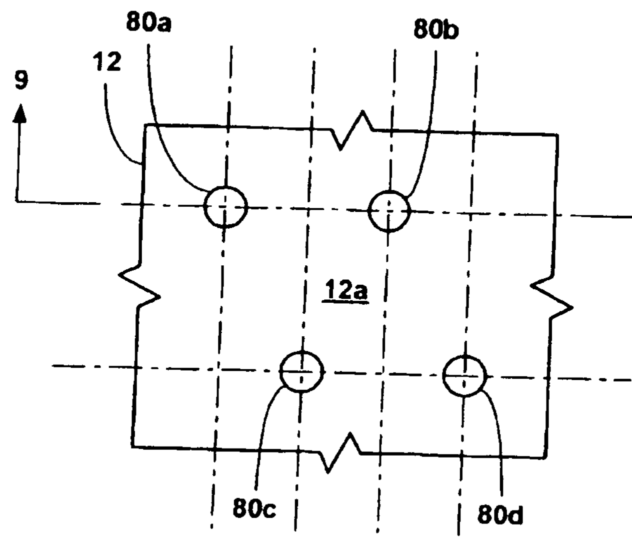


Fig. 8

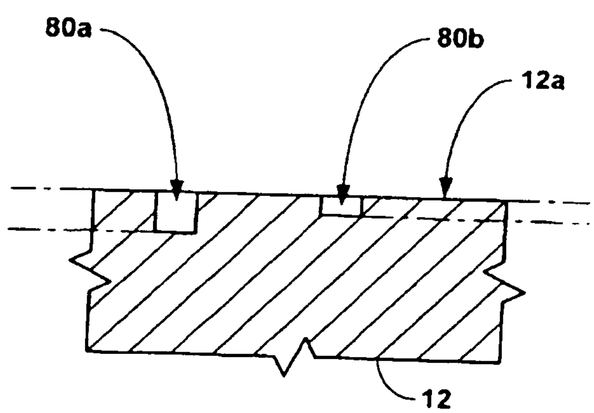


Fig. 9

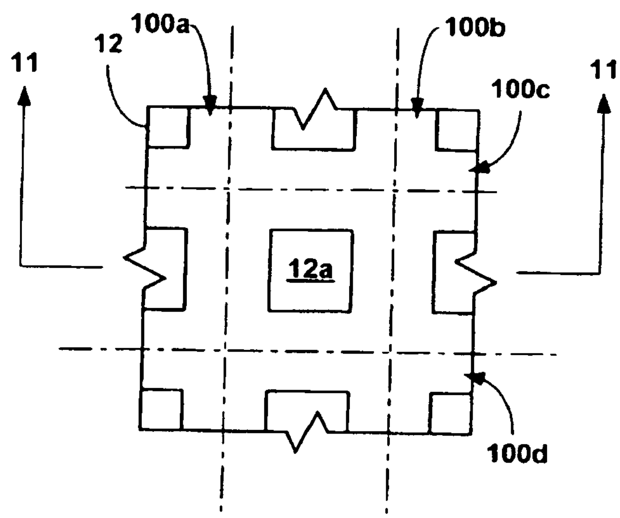


Fig. 10

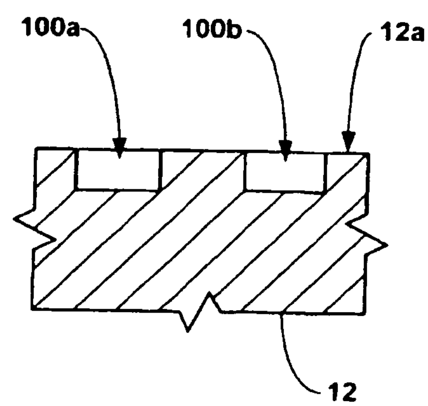


Fig. 11

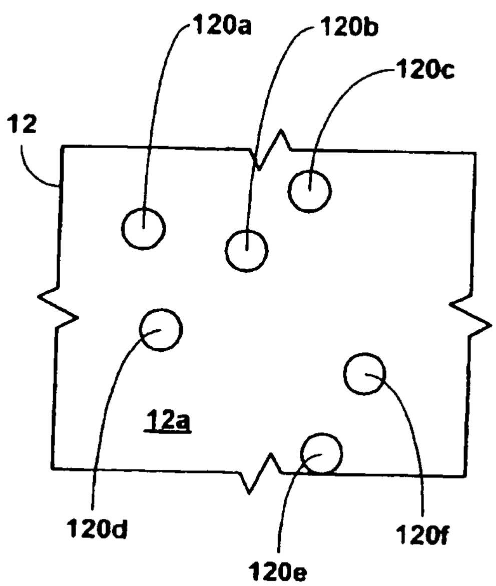
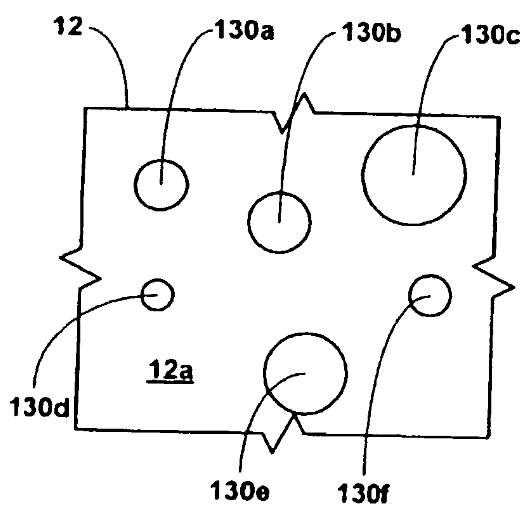

120a
120b
120c
12
12a
120d
120e
120f

Fig. 12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130a
130b
130c
12a
130d
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130f

Fig. 13

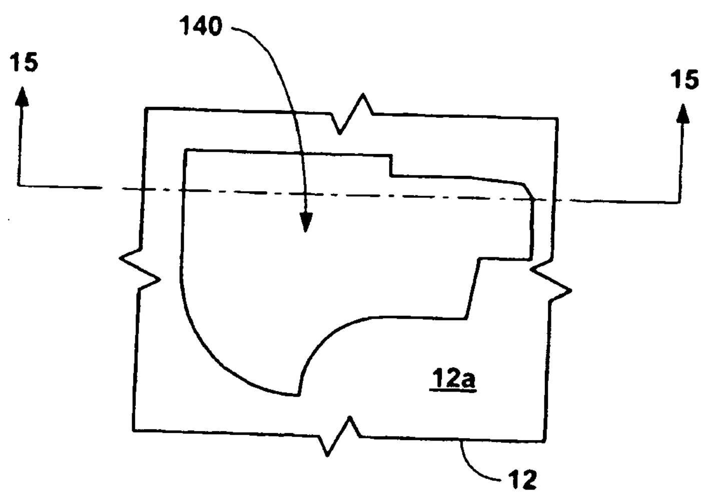


Fig. 14

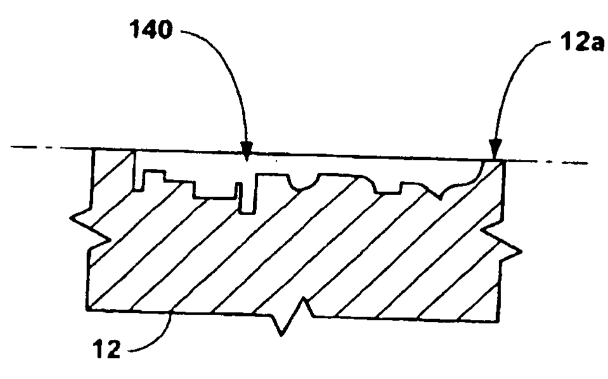


Fig. 15

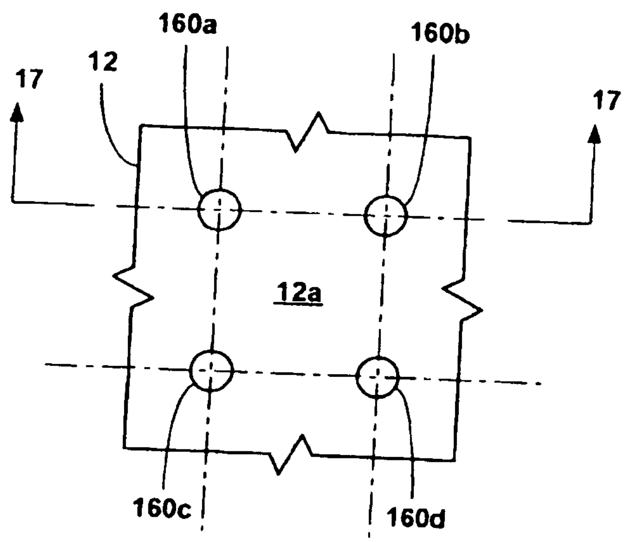


Fig. 16

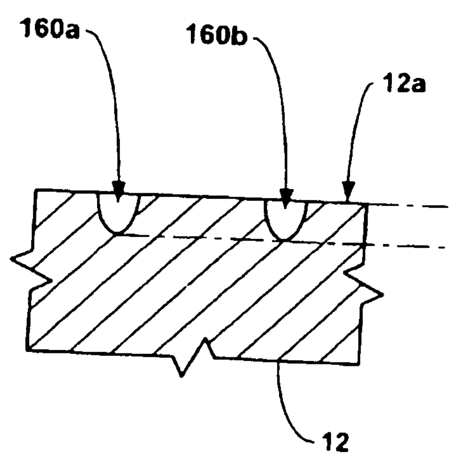


Fig. 17

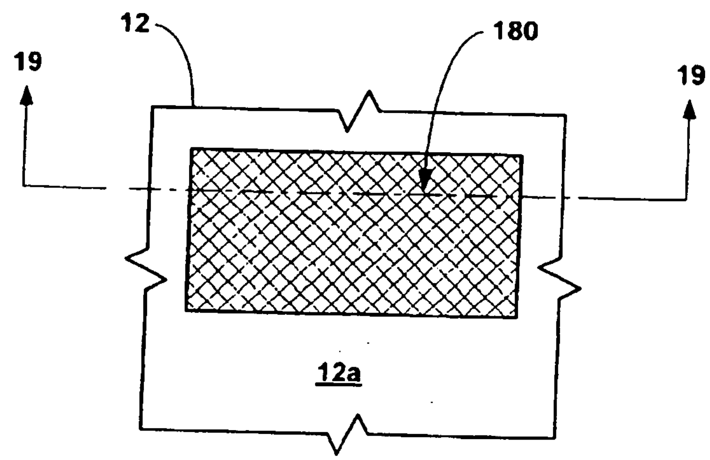


Fig. 18

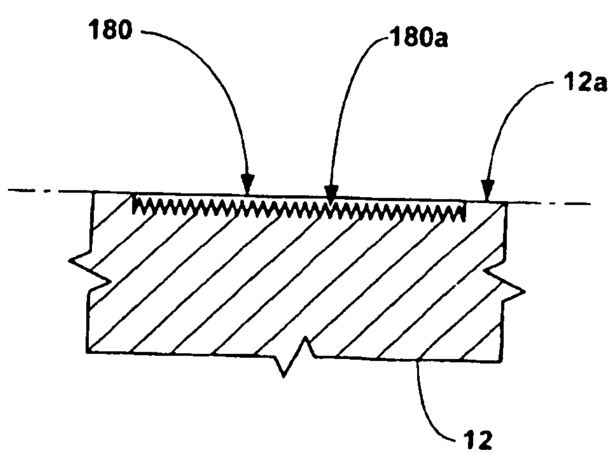


Fig. 19

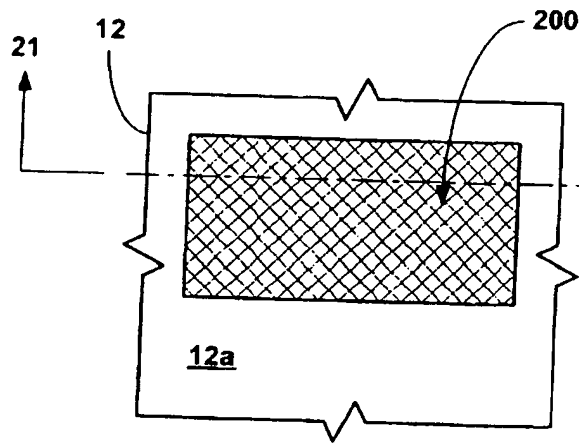


Fig. 20

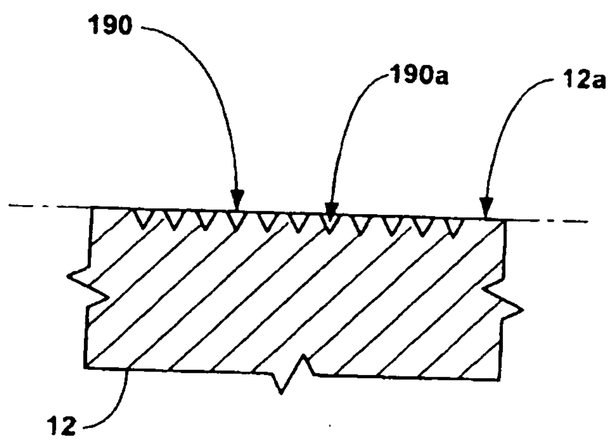


Fig. 21

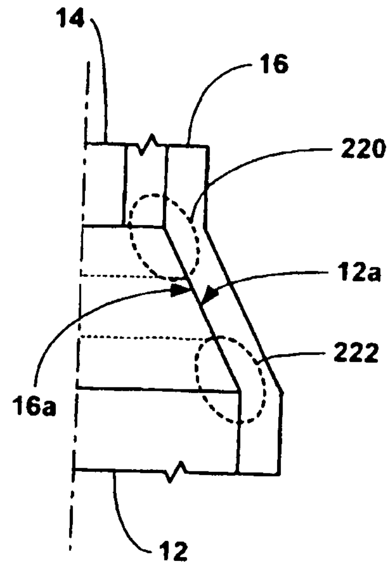

14
16
220
12a
222
16a
12

Fig. 22

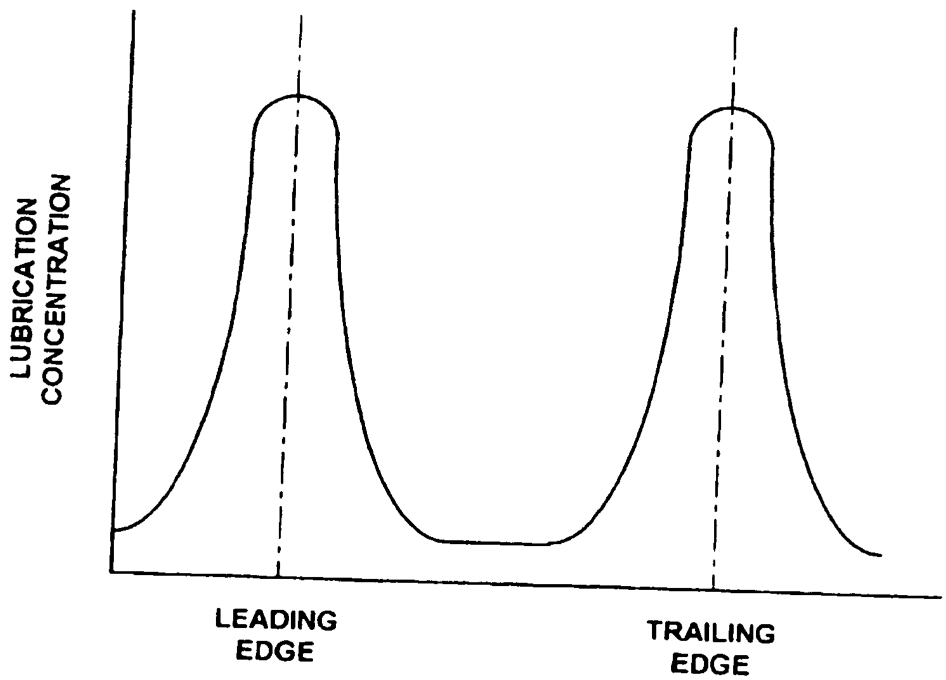

LUBRICATION
CONCENTRATION
LEADING
EDGE
TRAILING
EDGE

Fig. 23

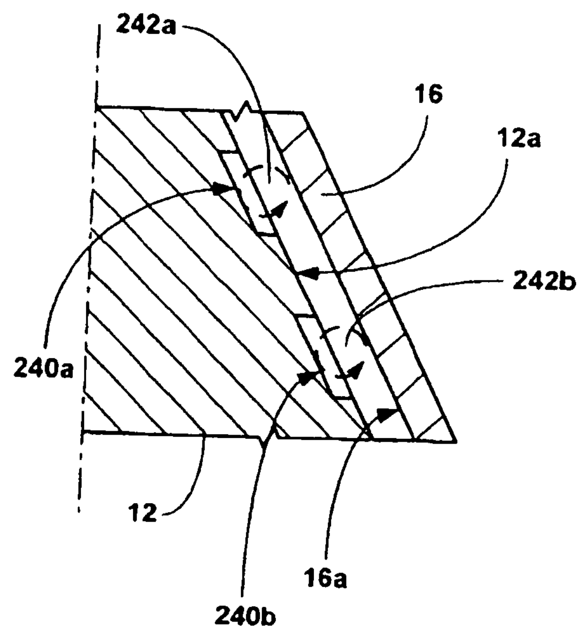

242a
16
12a
242b
240a
12
16a
240b

Fig. 24

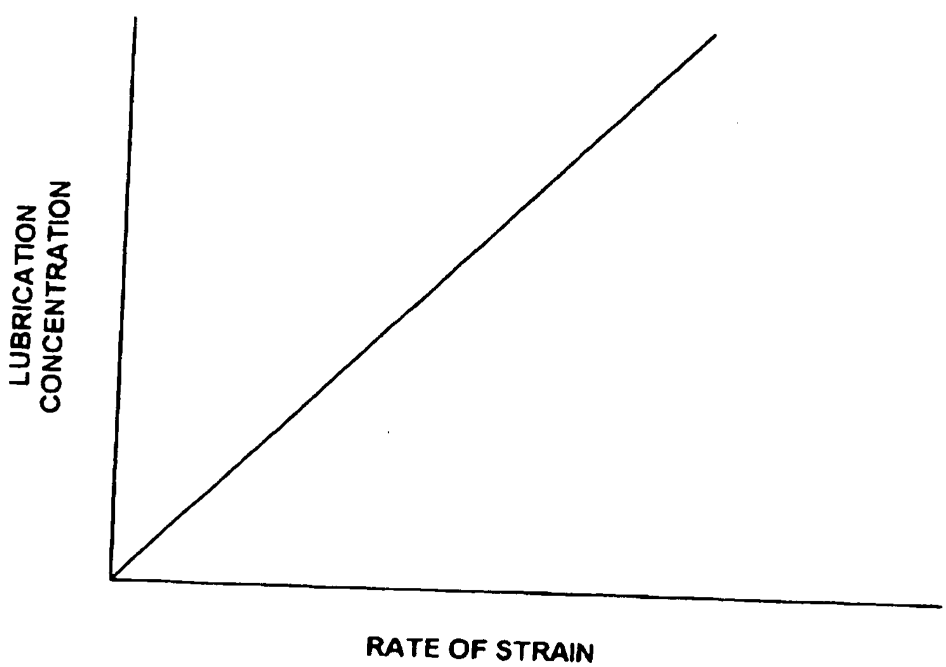
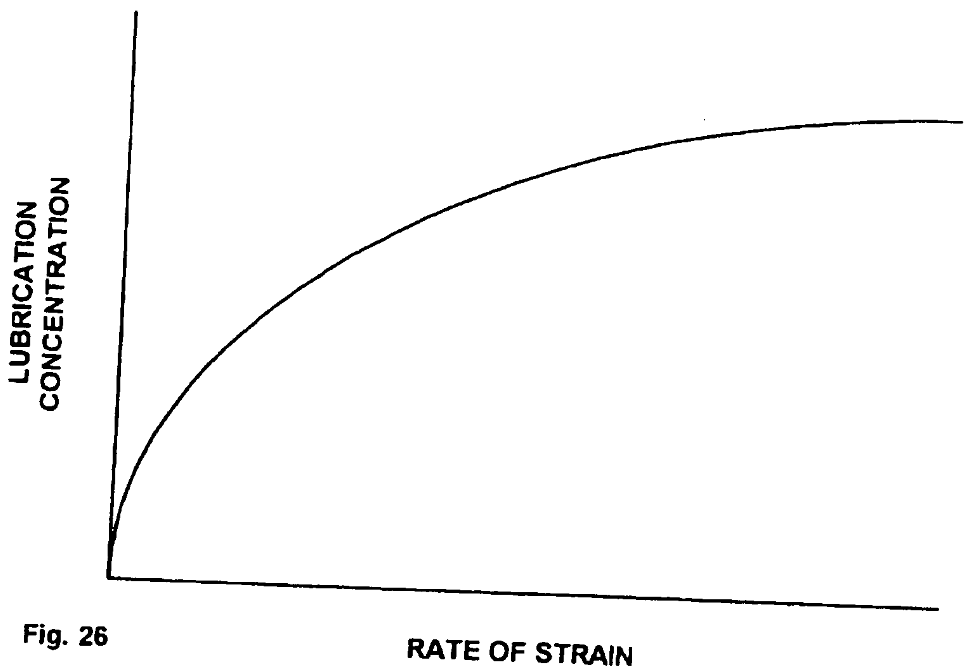
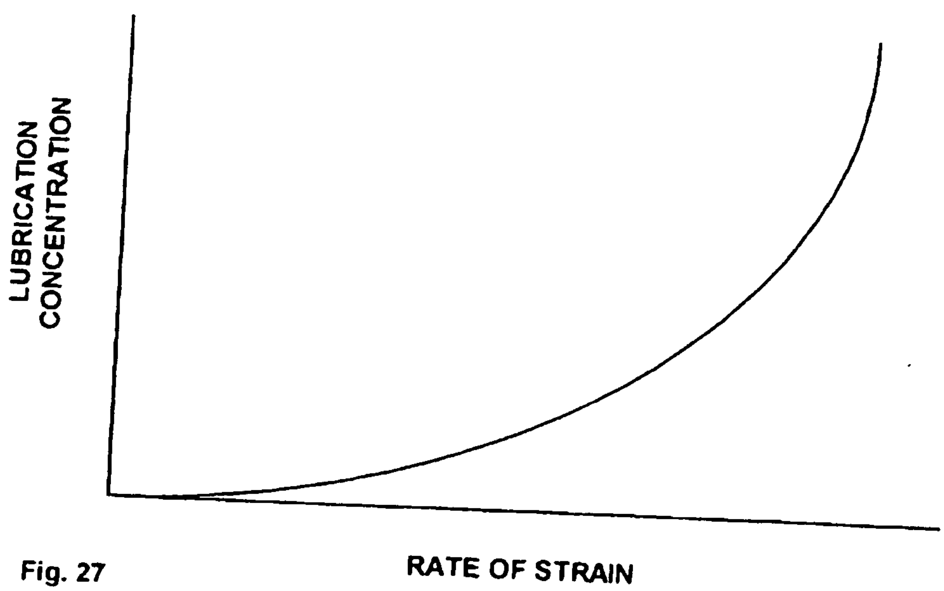
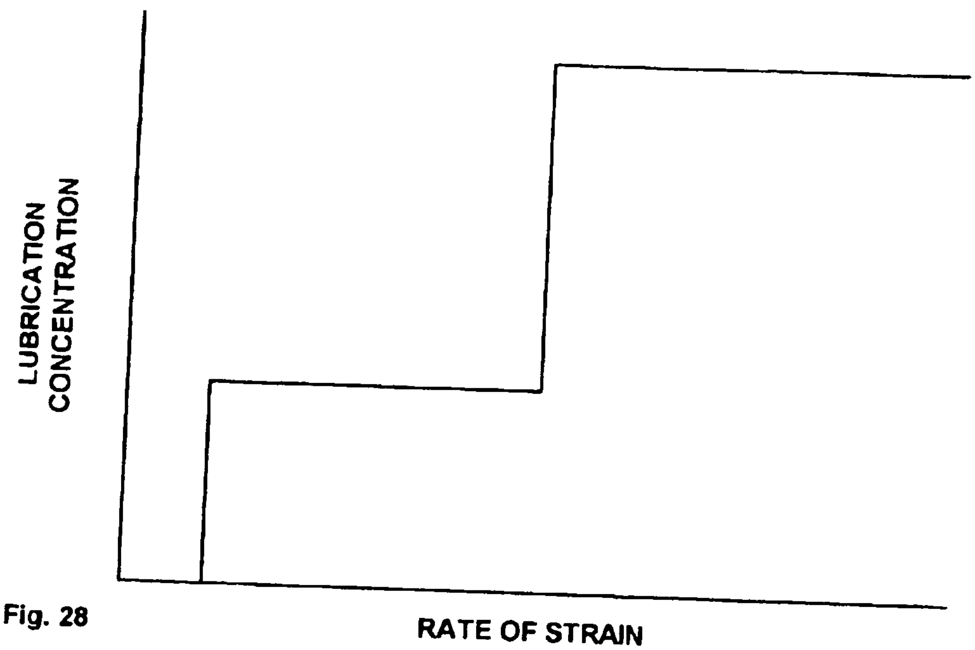
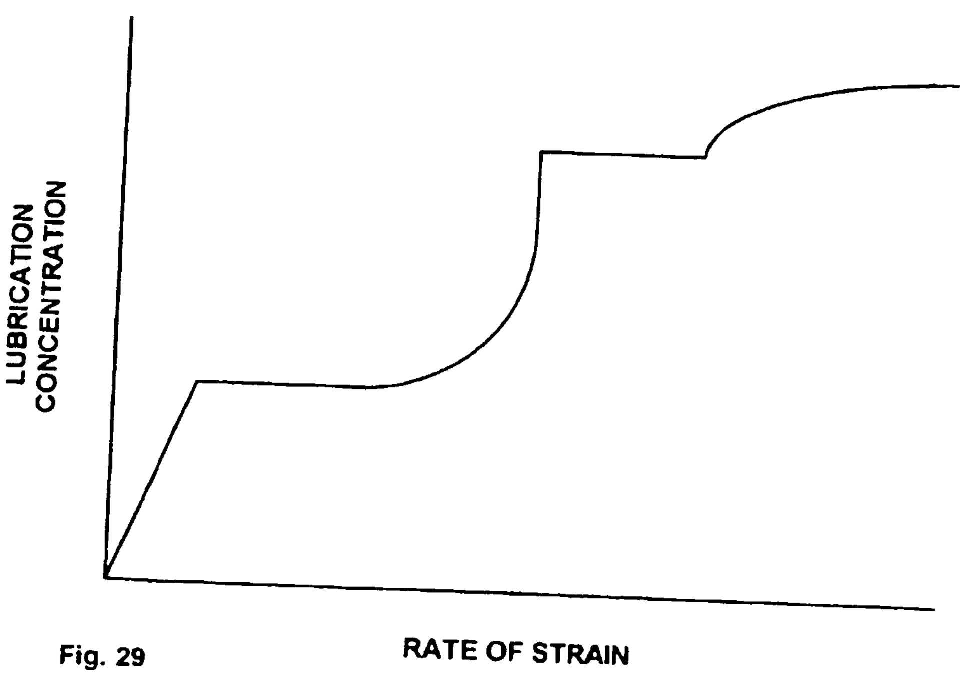

LUBRICATION CONCENTRATION
RATE OF STRAIN

Fig. 25


LUBRICATION
CONCENTRATION
RATE OF STRAIN
Fig. 26


LUBRICATION
CONCENTRATION
RATE OF STRAIN
Fig. 27


LUBRICATION CONCENTRATION
RATE OF STRAIN
Fig. 28


LUBRICATION CONCENTRATION
RATE OF STRAIN
Fig. 29

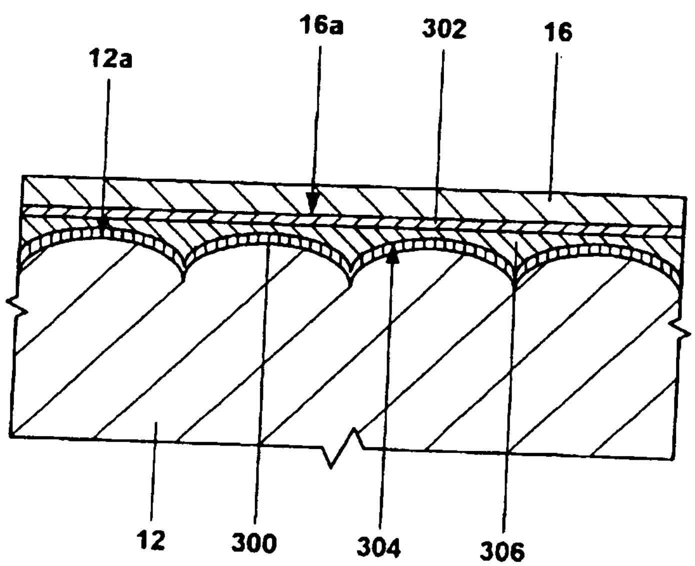


Fig. 30

Typical 3-D Surface View of the Conventional D2 Steel Cone after Multiple Expansion of the 1-5/8" Pipe

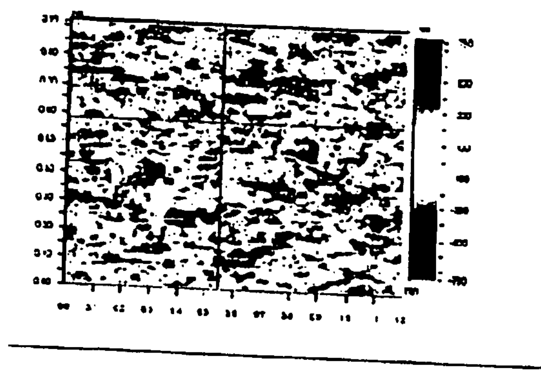


Fig. 31c

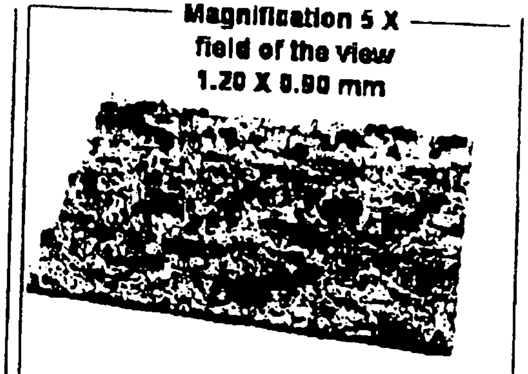


Fig. 31a

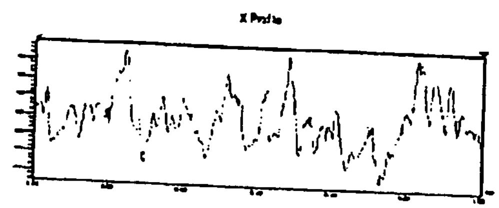


Fig. 31d

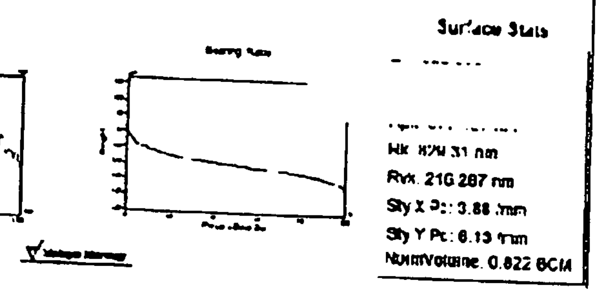
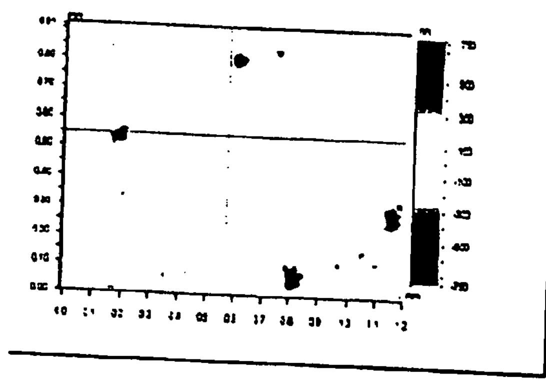


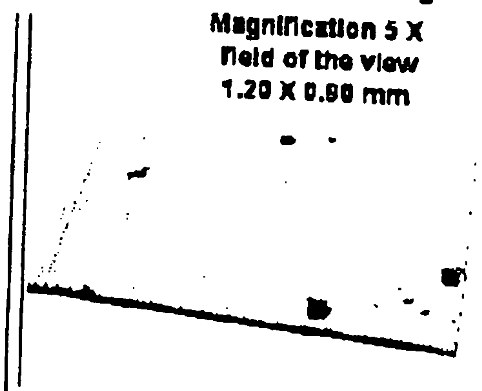
Fig. 31b

Fig. 32c

Fig. 32a

Typical 3-D Surface View of the Used Advanced DC53 Steel Cone with Phygen Film and REM Polishing





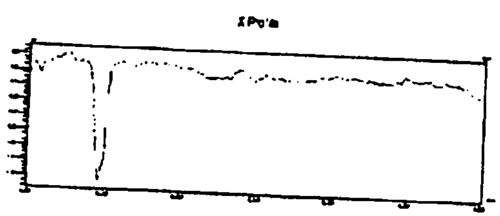
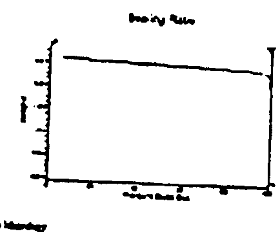


Fig. 32d



Surface Stats

Ra: 60.205 nm
Rz: 1.93 um
Rpk: 25.009 nm
Rk: 152.12 nm
Rvk: 92.963 nm
Sty X Pc: 2.21 /mm
Sty Y Pc: 3.53 /mm
NormVolume: 0.047 BCM

Fig. 32b

330

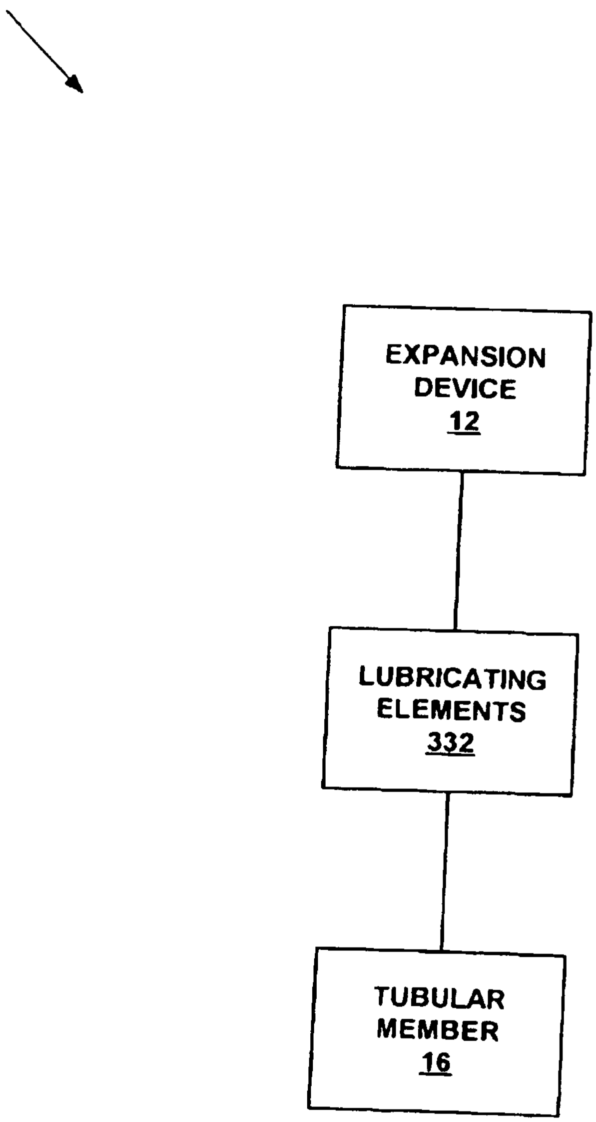

EXPANSION DEVICE 12
LUBRICATING ELEMENTS 332
TUBULAR MEMBER 16

Fig. 33

2433281

LUBRICATION SYSTEM FOR RADIALLY EXPANDING TUBULAR MEMBERS

Cross Reference To Related Applications

The present application claims the benefit of the filing date of U.S. provisional patent application serial no. 60/442,938, attorney docket no. 25791.225, filed on January 27, 2003.

The present application is related to the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, now U.S. Patent No. 6,497,289 issued 12-24-2002, (2) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, now U.S. Patent No. 6,328,113 issued 12-11-2001, (3) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, now U.S. Patent No. 6,568,471 issued 05-27-2003, (4) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, now U.S. Patent No. 6,575,240 issued 06-10-2003, (5) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, now U.S. Patent No. 6,557,640 issued 05-06-2003, (6) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, now U.S. Patent No. 6,604,763 issued 08-12-2003, (7) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, published as publication no. WO/2001/004535 on January 18, 2001, (8) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, now U.S. Patent No. 6,634,431 issued 10-21-2003, and (9) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, published as publication no. US2002-0121372 A1 on 09-05-2002, the disclosures of which are incorporated herein by reference.

Background of the Invention

This invention relates generally to oil and gas exploration, and in particular to forming and repairing wellbore casings to facilitate oil and gas exploration.

During oil exploration, a wellbore typically traverses a number of zones within a subterranean formation. Wellbore casings are then formed in the wellbore by radially expanding and plastically deforming tubular members that are coupled to one another by threaded connections. Existing methods for radially expanding and plastically deforming tubular members coupled to one another by threaded connections are not always reliable or produce satisfactory results. In particular, the threaded connections can be damaged during the radial expansion process.

During expansion, an expansion cone is moved axially through the tubular members. The cone has an outside diameter greater than the inside diameter of the tubular members. Thus, a tremendous amount of friction exists between the cone and the tubular members which results in heat, stress and wear.

The expansion cone, or mandrel, is used to permanently mechanically deform the pipe. The cone is moved through the tubing by a differential hydraulic pressure across the cone itself, and/or by a direct mechanical pull or push force. The differential pressure is pumped through an inner-string connected to the cone, and the mechanical force is applied by either raising or lowering the inner string.

Progress of the cone through the tubing deforms the steel beyond its elastic limit into the plastic region, while keeping stresses below ultimate yield.

Contact between cylindrical mandrel and pipe ID during expansion leads to significant forces due to friction. It would be beneficial to provide a mandrel which could reduce friction during the expansion process.

The present invention is directed to overcoming one or more of the limitations of the existing processes for radially expanding and plastically deforming tubular members coupled to one another by threaded connections.

Summary Of The Invention

According to one aspect of the present invention, a tribological system of lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member is provided that includes an expansion surface coupled to the expansion device defining a surface texture, a first lubricating film coupled to the expansion surface, a second lubricating film coupled to an interior surface of the tubular member, and a lubricating material disposed within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

In an exemplary embodiment, a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film. In an exemplary embodiment, the Ra for the expansion surface is less than or equal to 60.205 nm. In an exemplary embodiment, the Rz for the expansion surface is less than or equal to 1.99 nm. In an exemplary embodiment, the Ra for the expansion surface is about 60.205 nm. In an exemplary embodiment, the Rz for the expansion surface is about 1.99 nm. In an exemplary embodiment, the Ra for the expansion surface is less than or equal to 277.930 nm. In an exemplary embodiment, the Rz for

the expansion surface is less than or equal to 3.13 nm. In an exemplary embodiment, the Ra for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm. In an exemplary embodiment, the Rz for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm. In an exemplary embodiment, the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses. In an exemplary embodiment, the first lubricating film comprises chromium nitride. In an exemplary embodiment, the second lubricating film comprises PTFE. In an exemplary embodiment, the expansion surface comprises DC53 tool steel. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.125. In an exemplary embodiment, the coefficient of friction for the interface is less than 0.125. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.125 and greater than or equal to 0.06. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.06. In an exemplary embodiment, the expansion surface comprises a polished surface. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% and greater than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the bearing ratio of the expansion surface varies less than about 15%. In an exemplary embodiment, the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the Rz surface roughness.

According to anther aspect of the present invention, a method of lubricating an interface between an expansion surface of an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member is provided

that includes texturing the expansion surface, coupling a first lubricating film to the expansion surface, coupling a second lubricating film to an interior surface of the tubular member, and disposing a lubricating material within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

In an exemplary embodiment, a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film. In an exemplary embodiment, the Ra for the expansion surface is less than or equal to 60.205 nm. In an exemplary embodiment, the Rz for the expansion surface is less than or equal to 1.99 nm. In an exemplary embodiment, the Ra for the expansion surface is about 60.205 nm. In an exemplary embodiment, the Rz for the expansion surface is about 1.99 nm. In an exemplary embodiment, the Ra for the expansion surface is less than or equal to 277.930 nm. In an exemplary embodiment, the Rz for the expansion surface is less than or equal to 3.13 nm. In an exemplary embodiment, the Ra for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm. In an exemplary embodiment, the Rz for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm. In an exemplary embodiment, the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses. In an exemplary embodiment, the first lubricating film comprises chromium nitride. In an exemplary embodiment, the second lubricating film comprises PTFE. In an exemplary embodiment, the expansion surface comprises DC53 tool steel. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.125. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.125 and greater than or equal to 0.06. In an exemplary embodiment, the coefficient of friction for the interface is less than 0.125 and greater than or equal to 0.06. In an exemplary embodiment, the coefficient of friction for the interface is less or equal to 0.06. In an exemplary embodiment, the method further includes polishing the expansion surface. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member. In an

exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% and greater than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the bearing ratio of the expansion surface varies less than about 15%. In an exemplary embodiment, the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the Rz surface roughness.

Brief Description of the Drawings

Fig. 1a is a fragmentary cross-sectional view illustrating an exemplary embodiment of an apparatus for radially expanding and plastically deforming a tubular member.

Fig. 1b is a fragmentary cross-sectional illustration of an exemplary embodiment of the operation of the apparatus of Fig. 1a..

Fig. 2 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant supply.

Fig. 3 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant supply.

Fig. 4 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant coating.

Fig. 5 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant coating.

Fig. 6 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 7 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 6.

Fig. 8 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 9 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 8.

Fig. 10 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 11 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 10.

Fig. 12 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 13 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 12.

Fig. 14 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 15 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 14.

Fig. 16 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 17 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 16.

Fig. 18 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 19 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 18.

Fig. 20 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

Fig. 21 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 20.

Fig. 22 is a fragmentary cross-sectional illustration of an exemplary embodiment of leading and trailing edges of the interface between the expansion device of the apparatus of Figs. 1a and 1b and the tubular member during the radial expansion and plastic deformation of the tubular member.

Fig. 23 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

Fig. 24 is a fragmentary cross-sectional illustration of an exemplary embodiment of the interface between the expansion device of the apparatus of Figs. 1a and 1b and the tubular member during the radial expansion and plastic deformation of the tubular member.

Fig. 25 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

Fig. 26 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

Fig. 27 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

Fig. 28 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

Fig. 29 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

Fig. 30 is an exemplary embodiment of the apparatus of Figs. 1a and 1b.

Figs. 31a, 31b, 31c, and 31d are illustrations of an exemplary embodiment of the apparatus of Figs. 1a and 1b.

Figs. 32a, 32b, 32c, and 32d are illustrations of an exemplary embodiment of the apparatus of Figs. 1a and 1b.

Fig. 33 is a schematic illustration of a tribological system.

Detailed Description of the Illustrative Embodiments

Referring to Figs. 1a and 1b, an exemplary embodiment of an apparatus 10 for radially expanding a tubular member includes an expansion device 12 including one or more expansion surfaces 12a that is coupled to an end of a support member 14.

In an exemplary embodiment, the expansion device 12 is a conventional commercially available expansion device and/or is provided substantially as described in one or more of the following: : (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, now U.S. Patent No. 6,497,289 issued 12-24-2002, , (2) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, now U.S. Patent No. 6,328,113 issued 12-11-2001, (, (3) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, now U.S. Patent No. 6,568,471 issued 05-27-2003, (4) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, now U.S. Patent No. 6,575,240 issued 06-10-2003, (5) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, now U.S. Patent No. 6,557,640 issued 05-06-2003, (6) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, now U.S. Patent No. 6,604,763 issued 08-12-2003, (7) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, published as publication no. WO/2001/004535 on January 18, 2001, (8) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, now U.S. Patent No. 6,634,431 issued 10-21-2003, (9) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, published as publication no. US2002-0121372 A1 on 09-05-2002, the disclosures of which are incorporated herein by reference. In several alternative embodiments, the expansion device 12 is, or includes, a conventional commercially available rotary expansion device such, for example, those available from Weatherford International.

In an exemplary embodiment, the apparatus 10 is operated to radially expand and plastically deform a tubular member 16 by displacing and/or rotating the expansion device 12 relative to the tubular member 16 within a preexisting structure such as, for example, a wellbore 18 that traverses a subterranean formation 20. In an exemplary

embodiment, during the operation of the apparatus 10, the expansion surface 12a of the expansion device 12 engages at least a portion of the interior surface 16a of the tubular member 16.

In an exemplary embodiment, the apparatus 10 is operated substantially as described in one or more of the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, now U.S. Patent No. 6,497,289 issued 12-24-2002, (2) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, now U.S. Patent No. 6,328,113 issued 12-11-2001, , (3) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, now U.S. Patent No. 6,568,471 issued 05-27-2003, (4) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, now U.S. Patent No. 6,575,240 issued 06-10-2003, (5) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, now U.S. Patent No. 6,557,640 issued 05-06-2003, (6) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, now U.S. Patent No. 6,604,763 issued 08-12-2003 (7) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, published as publication no. WO/2001/004535 on January 18, 2001 (8) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, now U.S. Patent No. 6,634,431 issued 10-21-2003, (9) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, published as publication no. US2002-0121372 A1 on 09-05-2002, the disclosures of which are incorporated herein by reference. In several alternative embodiments, the expansion device 12 is operated like, or includes operational features of, a conventional commercially available rotary expansion device such, for example, those available from Weatherford International.

In an exemplary embodiment, as illustrated in Fig. 2, the apparatus 10 further includes a lubricant supply 20, and during the operation of the apparatus 10, the lubricant supply injects a lubricating material 22 into an annulus 24 defined between one or more the expansion surfaces 12a of the expansion device 12 and the internal surface 16a of the tubular member 16. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using

the expansion device 12 is reduced. In an exemplary embodiment, the lubricating material 22 includes fluidic and/or solid lubricating materials.

In an exemplary embodiment, as illustrated in Fig. 3, the expansion device 12 of the apparatus 10 further includes an internal lubricant supply 30, and during the operation of the apparatus 10, the lubricant supply injects a lubricating material 32 into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating material 32 includes fluidic and/or solid lubricating materials. In an exemplary embodiment, the lubricant supply injects the lubricating material 32 into one or more recesses defined in the expansion surface 12a of the expansion device 12.

In an exemplary embodiment, as illustrated in Fig. 4, a layer of a lubricating film 40 is coupled to at least a portion of one or more of the expansion surfaces 12a of the expansion device 12 of the apparatus 10 such that, during the operation of the apparatus, at least a portion of the lubricating film 40 is released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating film 40 includes fluidic and/or solid lubricating materials. In an exemplary embodiment, the thickness and/or composition of the film 40 are non-uniform.

In an exemplary embodiment, as illustrated in Fig. 5, layers 50a and 50b of a lubricating film are coupled to portions of one or more of the expansion surfaces 12a of the expansion device 12 of the apparatus 10 such that, during the operation of the apparatus, at least a portion of the layers of lubricating film, 50a and 50b, are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the layers, 50a and 50b, of lubricating film are deposited within recesses, 52a and 52b, respectively, defined within the expansion surface 12a. In an exemplary embodiment, the lubricating film, 50a and 50b, include fluidic and/or solid lubricating materials. In an exemplary embodiment, the thickness and/or composition of the films, 50a and/or 50b, are non-uniform.

In an exemplary embodiment, as illustrated in Figs. 6 and 7, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 60a, 60b, 60c, and 60d, that may, for example, contain the lubricant material 22, the lubricant material 32,

the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 60a, 60b, 60c, and 60d, are substantially identical and equally spaced cylindrical cavities defined within the expansion surface 12a of the expansion device. In several alternative embodiments, one or more of the recesses 60 may be different in geometry from one or more of the other recesses 60. In several alternative embodiments, the spacing between the recesses 60 may be unequal.

In an exemplary embodiment, as illustrated in Figs. 8 and 9, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 80a, 80b, 80c, and 80d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 80a, 80b, 80c, and 80d, are cylindrical cavities of varying depths defined within the expansion surface 12a of the expansion device. In an exemplary embodiment, the placement of the recesses 80 is such that the pair of recesses, 80a and 80b, are offset from the other pair of recesses, 80c and 80d. In several alternative embodiments, one or more of the recesses 80 may be different in geometry from one or more of the other recesses 80. In several alternative embodiments, the spacing between the recesses 80 may be unequal.

In an exemplary embodiment, as illustrated in Figs. 10 and 11, one or more portions of the expansion surfaces 12a of the apparatus 10 define criss-crossing recesses 100a, 100b, 100c, and 100d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 100a and 100b, are substantially parallel to one another,

and the recesses, 100c and 100d, are substantially parallel to one another, and the recesses, 100a and 100b, are both substantially orthogonal to the recesses, 100c and 100d. In several alternative embodiments, one or more of the recesses 100 may be different in geometry and orientation from one or more of the other recesses 100. In several alternative embodiments, the spacing between the recesses 100 may be unequal.

In an exemplary embodiment, as illustrated in Fig. 12, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 120a, 120b, 120c, 120d, 120e and 120f, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses 120 are substantially identical cylindrical recesses that are defined within, and randomly distributed on, the expansion surface 12a of the expansion device 12. In several alternative embodiments, one or more of the recesses 120 may be different in geometry and orientation from one or more of the other recesses 120.

In an exemplary embodiment, as illustrated in Fig. 13, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 130a, 130b, 130c, 130d, 130e and 130f, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses 130 are cylindrical recesses that are defined within, and randomly distributed on, the expansion surface 12a of the expansion device 12. In an exemplary embodiment, the volumetric geometry of the recesses 130 are randomly selected.

In an exemplary embodiment, as illustrated in Figs. 14 and 15, one or more portions of the expansion surfaces 12a of the apparatus 10 define one or more recesses 140, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the

lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the boundaries of the recess 140 include one or more linear and/or non-linear boundaries and the depth of the recess is random in all directions. In several alternative embodiments, one or more of the recesses 140 may be different in geometry and orientation from one or more of the other recesses 140. In several alternative embodiments, the spacing between the recesses 140 may be unequal and/or random. In several alternative embodiments, the depth of the recess 140 may be constant.

In an exemplary embodiment, as illustrated in Figs. 16 and 17, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 160a, 160b, 160c, and 160d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 160a, 160b, 160c, and 160d, are substantially identical and equally spaced cylindrical cavities having completely curved walls defined within the expansion surface 12a of the expansion device. In several alternative embodiments, one or more of the recesses 160 are substantially identical in geometry to the dimples found in one or more conventional golf balls. In several alternative embodiments, one or more of the recesses 160 may be different in geometry from one or more of the other recesses 160. In several alternative embodiments, the spacing between the recesses 160 may be unequal.

In an exemplary embodiment, as illustrated in Figs. 18 and 19, one or more portions of the expansion surfaces 12a of the apparatus 10 define a recess 180, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recess 180 is an

etched surface having a non-uniform pattern of pits 180a. In several alternative embodiments, the depth of the pits 180a is non-uniform.

In an exemplary embodiment, as illustrated in Figs. 20 and 21, one or more portions of the expansion surfaces 12a of the apparatus 10 define a recess 190, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recess 190 is a knurled surface having a uniform pattern of pits 190a. In several alternative embodiments, the pattern of the pits 190a and/or the depth of the pits 190a is non-uniform.

In an exemplary embodiment, as illustrated in Fig. 22, during the operation of the apparatus 10, the interface between the expansion surface 12a of the expansion device 12 and the interior surface 16a of the tubular member 16 includes a leading edge portion 220 and a trailing edge portion 222. In an exemplary embodiment, as illustrated in Fig. 23, the concentration of lubrication is increased in the leading and trailing edge portions, 220 and 222, respectively, in order to reduce the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12.

In several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is increased by increasing one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

In an exemplary embodiment, as illustrated in Fig. 24, during the operation of the apparatus 10, recesses, 240a and 240b, defined within the expansion surface 12a of the expansion device 12, provide a support for, and define lubrication ball bearings, 242a and 242b, for lubricating the interface between the expansion surface of the expansion device and the internal surface 16a of the tubular member. In this manner, the lubricating materials derived from one or more of the following: the lubricant

materials 22 and/or 32 and/or the films 40 and/or 50 are formed into a ball-like fluidic lubricating structure that act like lubricating ball bearings thereby reducing the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12.

In an exemplary embodiment, during the operation of the apparatus 10, the rate of strain of the tubular member 16 varies as a function of the geometry of the expansion surface 12a of the expansion device. Thus, for example, certain portions of the tubular member 16 that interface with the expansion surface 12a of the expansion device 12 may experience rates of strain that are different from other portions of the tubular member that interface with the expansion surface of the expansion device. In an exemplary embodiment, during the operation of the apparatus 10, the concentration of lubrication is increased in those areas having greater rates of strain as compared with those areas having lesser rates of strain in order to reduce the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12. In an exemplary embodiment, as illustrated in Fig. 25, the relationship between the concentration of lubrication and the rate of strain is a linear relationship. In an alternative embodiment, as illustrated in Fig. 26, the relationship between the concentration of lubrication and the rate of strain is a non-linear relationship having a decreasing slope with increasing rate of strain. In an alternative embodiment, as illustrated in Fig. 27, the relationship between the concentration of lubrication and the rate of strain is a non-linear relationship having an decreasing slope with increasing rate of strain. In an alternative embodiment, as illustrated in Fig. 28, the relationship between the concentration of lubrication and the rate of strain includes one or more step functions. In an alternative embodiment, as illustrated in Fig. 29, the relationship between the concentration of lubrication and the rate of strain includes one or more of the characteristics of Figs. 25-28.

In several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is increased by increasing one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

More generally, in several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is controlled by adjusting one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

In several exemplary embodiments, during at least a portion of the operation of the apparatus 10, at least portions of the annulus 24 between the expansion surface 12a of the expansion device 12 and the internal surface 16a of the tubular member 16 may be reduced in thickness to zero thereby permitting the at least a portion of the expansion surface of the expansion device to contact at least a portion of the interior surface of the tubular member.

In several exemplary embodiments, the lubricating films 40 and/or 50 include a physical vapor deposition Chromium Nitride coating commercially available from Phygen, Inc, in Minneapolis, Minnesota. In several exemplary embodiments, the lubricating films 40 and/or 50 are coupled to an expansion surface 12a fabricated from DC53 steel, new cold die steel, commercially available from Daido Steel Co. in Japan and/or International Steel Co., in Florence, Kentucky.

In several exemplary embodiments, the surface texture of at least a portion of one or more of the expansion surfaces 12a and/or one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 is provided by polishing a surface roughness into the expansion surfaces and/or recesses using commercially available methods and apparatus available from REM Chemicals, in Brenham, Texas.

In several exemplary embodiments, the lubricant materials 22 and/or 32 include various environmentally friendly lubricant materials commercially available from Oleon, Inc. in Belgium and/or as lubricant materials # 2633-179 - 1, 2, 3, 4, 5, and 6 from Houghton International, Valley Forge, Pennsylvania. In several exemplary embodiments, the lubricant materials 22 and/or 32 include Radiagreen eme salt.

Referring to Fig. 30, in an exemplary embodiment, at least a portion of one or more of the expansion surfaces 12a of the expansion device 12 is textured and a lubricating film 300 is coupled to at least a portion of the textured expansion surface. Furthermore, in an exemplary embodiment, at least a portion of the interior surface 16a of the tubular member 16 includes a lubricating film 302, and an annulus 304 defined

between the expansion device 12 and the tubular member 16 includes a lubricant material 306. In an exemplary embodiment, the lubricating film 300 is harder and more resistant to abrasion than the lubricating film 302. In an exemplary embodiment, the use of a textured expansion surface 12a, the lubricating film 300, the lubricating film 302, and the lubricant film 306 during the operation of the apparatus 10 provided a friction coefficient less than about 0.02. In an exemplary embodiment, the textured expansion surface 12a is provided using one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 described above and/or by texturing the expansion surface 12a. In an exemplary embodiment, the expansion surface 12a is fabricated from a DC53 tool steel, commercially available from Daido Steel in Japan, the texturing of the expansion surface 12a is provided by polishing the expansion surface using the commercially available products and services of REM Chemicals in Brenham, Texas, the lubricating film 300 includes a hard film Phygen 2, physical vapor deposition Chromium Nitride coating, commercially available from Phygen, Inc., in Minneapolis, MN, the lubricating film 302 includes a Polytetrafluoroethylene (PTFE) based soft film coating, commercially available as a Brighton 9075 coating from Brighton Laboratories, in Howell, Michigan, and the lubricant material 306 includes a commercially available lubricant from Houghton International, in Valley Forge, Pennsylvania.

In an exemplary embodiment, the surface texture of the expansion surface 12a and/or one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 is characterized by one or more of the following parameters: R_a, R_q, R_{sk}, R_{ku}, R_p, R_v, R_t, R_{pm}, R_{vm}, R_z, R_{pk}, R_k, R_{vk}, M_{r1}, M_{r2}, R_{pk}/R_k, R_{vk}/R_k, R_{pk}/R_{vk}, X Slope R_q, Y Slope R_q, NVOL, and/or SAI. In an exemplary embodiment, the measurement of these parameters is provided using the commercially available services of Michigan Metrology LLC in Livonia, Michigan.

R_a refers to the arithmetic average of the absolute values of the surface height deviations measured from the best fitting plane, cylinder or sphere. Ra is described by:

$$R_a = \iint_a |Z(x,y)| dx dy$$

where Z(x,y) = the vertical position of a position on the surface at coordinates x and y

R_q refers to the RMS (Standard Deviation) or "first moment" of the height distribution, as described by:

$$Rq = \sqrt{\iint_a (Z(x,y))^2 dx dy}$$

R_{sk} refers to the skew or 'second moment" of the height distribution., as described by:

$$Rsk = \frac{1}{R_q^3}\iint_a (Z(x,y))^3\,dxdy$$

R_{ku} refers to the "kurtosis" or the "third moment" of the height distribution, described by:

$$R_{ku} = \frac{1}{R_q^4}\iint_a (Z(x,y))^4\,dxdy$$

R_p, R_v, and R_t are parameters evaluated from the absolute highest and lowest points found on the surface. R_p is the height of the highest point, R_v is the depth of the lowest point and R_t is found from Rp – Rv. The R_{pm}, R_{vm}, and R_z parameters are evaluated from an average of the heights and depths of the extreme peaks and valleys. R_{pm} is found by averaging the heights of the ten (10) highest peaks found over the complete 3D image. R_{vm} is found by averaging the depths of the ten (10) lowest valleys found over the complete 3D image. R_z is then found by (R_{pm}-R_{vm}).

The parameters Rpk, Rk, Rvk, Mr1, and Mr2 are all derived from the bearing ratio curve based on the DIN 4776 standard, the disclosure of which is incorporated herein by reference. The bearing area curve is a measure of the relative cross-sectional area a plane passing through the measured surface, from the highest peak to the lowest valley, would encounter. R_{pk} is a measure of the peak height above the nominal/core roughness. R_k is a measure of the nominal or "core" roughness ("peak to valley") of the surface. R_{vk} is a measure of the valley depth below the nominal /core roughness. M_{r1}, the peak material ratio, indicates the percentage of material that comprise the peak structures associate with R_{pk}. M_{r2} is a measure of the valley material ratio, with (100%-M_{r2}) representing the percentage of material that comprise the valley structures associated with R_{vk}.

R_{pk}/R_k, R_{vk}/R_k, R_{pk}/R_{vk}: the ratios of the various bearing ratio parameters may be helpful in further understanding the nature of a particular surface texture. In some instances two surfaces with indistinguishable average roughness (R_a) may be easily distinguished by the ratio such as R_{pk}/R_k. For example, a surface with high peaks as opposed to a surface with deep valleys may have the same R_a but with vastly different R_{pk}/R_k values.

X Slope R_q, Y Slope R_q: The parameters X Slope R_q and Y Slope R_q are found by calculating the Standard Deviation (i.e. RMS or R_q) of the slopes of the surface along

the X and Y directions respectively. The slope is found by taking the derivative of the surface profiles along each direction, using the lateral resolution of the measurement area as the point spacing. Analytically, X Slope R_q and Y Slope R_q are given by:

$$X\,Slope\,Rq = \left(\iint_a \left(\frac{\partial Z(x,y)}{\partial x} - \langle\frac{\partial Z(x,y)}{\partial x}\rangle\right)^2\right) \qquad Y\,Slope\,Rq = \left(\iint_a \left(\frac{\partial Z(x,y)}{\partial y} - \langle\frac{\partial Z(x,y)}{\partial y}\rangle\right)^2 dx\,dy\right)^{1/2}$$

Where the brackets, < >, represent the average value of all slopes in the relevant direction

NVOL: The Normalized Volume (NVOL) of the surface is found by calculating the volume contained by the surface and a "plane" that is placed near the top of the surface. The placement of the reference plane is typically done on a statistical basis to assure that the very high peak locations are not used as the reference point for the plane. Once the volume is calculated (e.g. in units of cm^3), the result is "normalized" to the cross sectional area of the plane (i.e. units of m^2). Other units of NVOL are BCM, which is an acronym for "Billions of Cubic Microns per Inch Squared".

The Surface Area Index (SAI) evaluates the surface area at the lateral resolution of the measured surface as compared to that of a perfectly flat/smooth surface. The calculation involves fitting triangular patches between the measured points and adding up the total area of all patches. A ratio is then formed of the total surface area measured and the nominal flat area of measurement. This analysis is a precursor to a complete fractal analysis of the surface. Since SAI is a ratio, it is a unit-less quantity.

In an exemplary embodiment, one or more of the parameters R_a, R_q, R_{sk}, R_{ku}, R_p, R_v, R_t, R_{pm}, R_{vm}, R_z, R_{pk}, R_k, R_{vk}, M_{r1}, M_{r2}, R_{pk}/R_k, R_{vk}/R_k, R_{pk}/R_{vk}, X Slope R_q, Y Slope R_q, NVOL, and/or SAI described above are defined as described at the following website: http://www.michmet.com, the disclosure of which is incorporated herein by reference.

In an exemplary implementation, an apparatus 10 having an expansion device 12 including an expansion surface 12a fabricated from conventional D2 steel was operated to expand a plurality of tubular members 16 fabricated from low carbon steel using a water base mud media as a lubricating material. Fig. 31a is top view of a portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31b is a magnified perspective view of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the

apparatus 10. Fig. 31c is a graphical illustration of the surface profile of a sliced portion of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31d is a graphical and tabular illustration of the bearing ratio, R_a, R_z, R_{pk}, R_k, R_{vk}, Sty X Pc (X Slope R_q), Sty Y Pc (Y Slope R_q), and NVOL for the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. As illustrated in Fig. 31d, the exemplary implementation had the following characteristics:

Parameter	**Value**
R_a	277.930 nm
R_z	3.13 nm
R_{pk}	377.167 nm
R_k	829.31 nm
R_{vk}	216.287 nm
Slope R_q	3.88/mm
Y Slope R_q	6.13/mm
NVOL	0.822 BCM

In the exemplary implementation of the embodiment of Figs. 31a, 31b, 31c, and 31d, the forces required to overcome friction during the operation of the apparatus 10 were about 45% of all the expansion forces required to radially expand and plastically deform the tubular member 16 and the coefficient of friction for the interface between the expansion surfaces 12a of the expansion device 12 and the interior surface 16a of the tubular member was about 0.125.

In an exemplary implementation, an apparatus 10 having an expansion device 12 including an expansion surface 12a fabricated from DC53 tool steel, available from Daido Steel in Japan, was operated to expand a plurality of tubular members 16 fabricated from low carbon steel. The expansion surface 12a was surface polished using the services of REM Chemicals in Brenham, Texas and a lubricating film including a Chromium Nitride coating, available from Phygen, Inc., in Minneapolis, Minnesota, was coupled to the expansion surface. Fig. 32a is top view of a portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32b is a magnified perspective view of the portion of the expansion

surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32c is a graphical illustration of the surface profile of a sliced portion of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32d is a graphical and tabular illustration of the bearing ratio, R_a, R_z, R_{pk}, R_k, R_{vk}, Sty X Pc (X Slope R_q), Sty Y Pc (Y Slope R_q), and NVOL for the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. As illustrated in Fig. 32d, the exemplary implementation had the following characteristics:

Parameter	**Value**
R_a	60.205 nm
R_z	1.99 nm
R_{pk}	25.009 nm
R_k	152.12 nm
R_{vk}	92.963 nm
Slope R_q	2.21/mm
Y Slope R_q	3.53/mm
NVOL	0.047 BCM

In the exemplary implementation of the embodiment of Figs. 32a, 32b, 32c, and 32d, the forces required to overcome friction during the operation of the apparatus 10 were between about 30% to 8% of all the expansion forces required to radially expand and plastically deform the tubular member 16 and the coefficient of friction for the interface between the expansion surfaces 12a of the expansion device 12 and the interior surface 16a of the tubular member was about 0.06. Furthermore, in the exemplary embodiment of Figs. 32a, 32b, 32c, and 32d, the bearing ratio of the expansion surface 12a of the expansion device 12 was greater than 75% on 60% of the R_z surface roughness.

A comparison of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d and the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d indicated that an example of a preferred surface texture for an expansion surface 12a of the expansion device 12 during the radial expansion and plastic deformation of the tubular member 16 was a surface texture having a plateau-like surface with relatively

deep recesses as provided in the exemplary implementation of Figs. 32a, 32b, 32c, and 32d. This was an unexpected result.

Furthermore, a comparison of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d and the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d also indicated that the expansion surface of the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d provided not only a smoother surface, as measured by R_a and/or R_z, but also provided much higher load capacity, as measured by the bearing ratio. Furthermore, the bearing ratio for the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d had much less variation in value that the bearing ratio for the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d. Thus, in a preferred embodiment, the bearing ratio varies less than about 15% across the expansion surface 12a. In addition, the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d provided a bearing ratio about double that of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d. For example, at the level of 60% R_z, the percentage of the material supporting a load on the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d was about 80% in comparison to about 37% for the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d.

In an exemplary embodiment, the preferred surface texture of the exemplary implementation of Figs. 32a, 32b, 32c, and 32d, a plateau-like surface with relatively deep recesses, is provided by laser dimpling the expansion surface 12a.

In an exemplary embodiment, as illustrated in Fig. 33, the apparatus 10 provides a tribological system 330 including the expansion device 12, the tubular member 16, and one or more lubricating elements 332 such as, for example, those elements described above for reducing friction between the expansion surfaces 12a of the expansion device and the tubular member during the operation of the apparatus 10. In an exemplary embodiment, the system 330 is designed and operated to minimize the friction between the expansion device 12 and the tubular member 16.

A tribological system of lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, a first lubricating film coupled to the expansion surface, a second lubricating film coupled to an interior surface of the tubular member, and a lubricating material disposed within an annulus defined between

the expansion surface of the expansion device and the interior surface of the tubular member.

A method of lubricating an interface between an expansion surface of an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes texturing the expansion surface, coupling a first lubricating film to the expansion surface, coupling a second lubricating film to an interior surface of the tubular member, and disposing a lubricating material within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

CLAIMS

1. A tribological system of lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

   an expansion surface coupled to the expansion device defining a surface texture;

   a first lubricating film coupled to the expansion surface;

   a second lubricating film coupled to an interior surface of the tubular member; and

   a lubricating material disposed within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

2. The system of claim 1, wherein a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film.

3. The system of claim 1, wherein the R_a for the expansion surface is less than or equal to 60.205 nm.

4. The system of claim 1, wherein the R_z for the expansion surface is less than or equal to 1.99 nm.

5. The system of claim 1, wherein the R_a for the expansion surface is about 60.205 nm.

6. The system of claim 1, wherein the R_z for the expansion surface is about 1.99 nm.

7. The system of claim 1, wherein the R_a for the expansion surface is less than or equal to 277.930 nm.

8. The system of claim 1, wherein the R_z for the expansion surface is less than or equal to 3.13 nm.

9. The system of claim 1, wherein the R_a for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm.

10. The system of claim 1, wherein the R_z for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm.

11. The system of claim 1, wherein the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses.

12. The system of claim 1, wherein the first lubricating film comprises chromium nitride.

13. The system of claim 1, wherein the second lubricating film comprises PTFE.

14. The system of claim 1, wherein the expansion surface comprises DC53 tool steel.

15. The system of claim 1, wherein the coefficient of friction for the interface is less than or equal to 0.125.

16. The system of claim 1, wherein the coefficient of friction for the interface is less than 0.125.

17. The system of claim 1, wherein the coefficient of friction for the interface is less than or equal to 0.125 and greater than or equal to 0.06.

18. The system of claim 1, wherein the coefficient of friction for the interface is less than or equal to 0.06.

19. The system of claim 1, wherein the expansion surface comprises a polished surface.

20. The system of claim 1, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member.

21. The system of claim 1, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member.

22. The system of claim 1, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% and greater than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

23. The system of claim 1, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

24. The system of claim 1, wherein the bearing ratio of the expansion surface varies less than about 15%.

25. The system of claim 1, wherein the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the R_z surface roughness.

26. A method of lubricating an interface between an expansion surface of an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

texturing the expansion surface;

coupling a first lubricating film to the expansion surface;

coupling a second lubricating film to an interior surface of the tubular member; and

disposing a lubricating material within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

27. The method of claim 26, wherein a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film.

28. The method of claim 26, wherein the R_a for the expansion surface is less than or equal to 60.205 nm.

29. The method of claim 26, wherein the R_z for the expansion surface is less than or equal to 1.99 nm.

30. The method of claim 26, wherein the R_a for the expansion surface is about 60.205 nm.

31. The method of claim 26, wherein the R_z for the expansion surface is about 1.99 nm.

32. The method of claim 26, wherein the R_a for the expansion surface is less than or equal to 277.930 nm.

33. The method of claim 26, wherein the R_z for the expansion surface is less than or equal to 3.13 nm.

34. The method of claim 26, wherein the R_a for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm.

35. The method of claim 26, wherein the R_z for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm.

36. The method of claim 26, wherein the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses.

37. The method of claim 26, wherein the first lubricating film comprises chromium nitride.

38. The method of claim 26, wherein the second lubricating film comprises PTFE.

39. The method of claim 26, wherein the expansion surface comprises DC53 tool steel.

40. The method of claim 26, wherein the coefficient of friction for the interface is less than or equal to 0.125.

41. The method of claim 26, wherein the coefficient of friction for the interface is less than or equal to 0.125 and greater than or equal to 0.06.

42. The method of claim 26, wherein the coefficient of friction for the interface is less than 0.125 and greater than or equal to 0.06.

43. The method of claim 26, wherein the coefficient of friction for the interface is less or equal to 0.06.

44. The method of claim 26, further comprising polishing the expansion surface.

45. The method of claim 26, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member.

46. The method of claim 26, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member.

47. The method of claim 26, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or

equal to 45% and greater than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

48. The method of claim 26, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

49. The method of claim 26, wherein the bearing ratio of the expansion surface varies less than about 15%.

50. The method of claim 26, wherein the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the R_z surface roughness.